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Article

Groundwater salinization in inland basins of arid and semiarid climates: An overview

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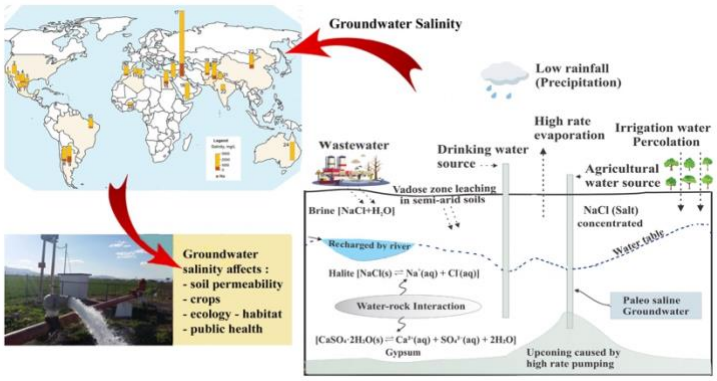

Highlights

- *Salinization of inland aquifers in semiarid areas is tied to evaporite dissolution.*
- *The highest groundwater salinity is found in the MENA region.*
- *Groundwater salinization increases faster in areas of intensive agriculture.*
- *Standardization of units of measurement is needed to assess and compare salinities.*
- *Water-saving irrigation and increased monitoring are desirable actions.*

Abstract

Salinization of aquifers is a growing global challenge in the aquifers ability to supply drinking and irrigation water, especially in regions with arid or semiarid climates. An analysis of key recent studies was conducted to identify the factors that lead to the severity of the salinity problem in vulnerable areas. The highest salinity values (averaging 2,000 mg/L to 12,000 mg/L) are reported for the Middle East and North Africa (MENA), resulting from the dissolution of carbonates, gypsum and halite. Intensive agriculture artificially raises the water table, favoring evaporation, which together with the infiltration of irrigation returns, significantly increases salinity. Latin American regions report unsustainable groundwater withdrawals and poor management as their main challenge. Overall, groundwater salinity evolves from Na-HCO_3 and Ca-HCO_3 types to Na-Cl type. Strategies aimed at reducing salinization consistently emphasize increased monitoring and effective water management practices, which vary according to each region. Two regions, northern Mexico and the food basket of Ghana, illustrate the differences and similarities of groundwater salinization in irrigated semiarid areas.

Abbreviations

EC – Electrical conductivity
MENA – Middle East and North Africa
NO_3-N – Nitrate-nitrogen
UN SDG – United Nations Sustainable Development Goals
TDS – Total dissolved solids
WRTDS – Weighted regressions on time, discharge, and season

1 Introduction

Groundwater, a limited resource in arid and semiarid areas, provides drinking water and contributes to the water used for food producing activities such as irrigation, dairy farming, and agroindustry. The latter activities make an otherwise barren land economically profitable; however, these areas

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face severe consequences for the future availability of the resource (Foster et al., 2018; Etikala et al., 2021). In arid and semiarid areas, groundwater resources are diminishing at a rapid rate because of excessive withdrawals, the inherent hardships to recharge the aquifers, especially during a drought (Scanlon et al., 2007; Scanlon et al., 2021; Etikala et al., 2021; Mora et al., 2021) and by increased contamination (Anning, 2011; MacDonald et al., 2016; Kaushal et al., 2018).

As the levels of aquifers decline and groundwater quality deteriorates, the demand for groundwater continues to increase, posing a challenge to the sustainability of the resource and to food production. Worldwide, irrigated land with salinization problems has been estimated to be approximately 65 million ha (Mateo-Sagasta and Albers, 2018) and it is more severe in arid and semiarid areas of developing countries (Li et al., 2020; Yang et al., 2022). According to global climate projections, arid and semiarid regions face warmer and drier conditions, compounding to the above groundwater problems (Kundzewicz, 2008; Etikala et al., 2021; Aouati et al., 2023; Bern et al., 2024; van Deelen, 2024). An additional problem in arid and semiarid areas, especially within developing countries, is the lack of an adequate amount of water level monitoring and water quality data that stakeholders require to make the best, sustainability-led, decisions (Yang et al., 2022; Aouati et al., 2023).

Salinization of groundwater occurs both in coastal areas and inland basins (e.g., Pulido-Bosh et al., 2018; Foster et al., 2018; Li et al., 2020; Yang et al., 2022; Fosu et al., 2025). Most times, salinity is reported indistinctively, despite differences in the groundwater flow, evaporation enrichment, and type of solutes among these two types of basins. To obtain an overview of the groundwater salinization of semiarid inland basins, 40 key research articles published between 2010 and 2025 were selected, analyzed, and incorporated into the review. The specific objectives of this review are to: (1) update the groundwater salinity status of affected inland basins, (2) identify specific conditions that lead to groundwater salinization in inland basins, and (3) report and assess the various methodologies utilized to quantify salinity and salinity trends.

The novelty of this study lies in its comprehensive approach to integrating diverse studies, highlighting the unique challenges faced by arid and semiarid regions, identifying gaps in current knowledge, and providing insights into the interplay between natural processes and human activities that exacerbate groundwater salinization of inland basins. The results constitute a critical resource for policymakers and researchers aiming to ensure sustainable groundwater use in these vulnerable regions. By addressing groundwater salinization, the review supports the United Nations Sustainable Development Goals (UN SDG), especially SDG 6 (Clean Water and Sanitation) by promoting sustainable management of water resources and improving water quality. It also aligns with SDG 2 (Zero Hunger) by ensuring the availability of clean water for agriculture. Furthermore, the review's insights into mitigating salinization can help reduce poverty (SDG 1) by protecting livelihoods dependent on agriculture and water resources. Additionally, by fostering sustainable practices, the review indirectly supports SDG 13 (Climate Action) by enhancing resilience to climate-related impacts on water resources.

2 Surface water – groundwater connection

Water resources of arid and semiarid areas are limited, fragile, and particularly vulnerable to climate change, and where a decrease in rainfall and an increase in the rate of evaporation have been predicted for the future (Kundzewicz, 2008; Hamed et al., 2024). These climatic changes imply a concurrent reduction in aquifer recharge and increase in groundwater salinity. The most vulnerable areas as with respect to salinization are agricultural areas with an arid to semiarid climate (Pulido-Bosh et al., 2018; Foster et al., 2018, Yang et al., 2022). In agricultural areas, extraction of groundwater for irrigation tends to increase during a drought due to surface reservoirs declining, causing aquifer levels to decrease when they are already naturally low and making recovery difficult (Scanlon et al., 2007). Also, a substantial part of the water may infiltrate back into the shallow aquifer, a form of induced recharge that commonly transports solutes from the surface to the aquifer (Anning, 2011; Scanlon et al., 2021; Bouimouass et al., 2022). **Figure 1** illustrates these processes.

Surface water contamination follows an increasing trend in concentration (Kaushal et al., 2018; Bern et al., 2024) that is caused, at least in part, by the discharge of salt-laden groundwater into streams (Bern et al., 2024). The opposite direction of contaminant flow also occurs when contaminated surface water infiltrates into the underlying aquifers, a direction favored by high groundwater extraction rates (MacDonald et al., 2016; Espino-Valdés et al., 2024).

Data sources to monitor salinization include satellite imagery, field surveys, and groundwater quality measurements. Remote sensing data can be processed to derive surface reflectance patterns using a combination of different spectral bands that can specifically determine

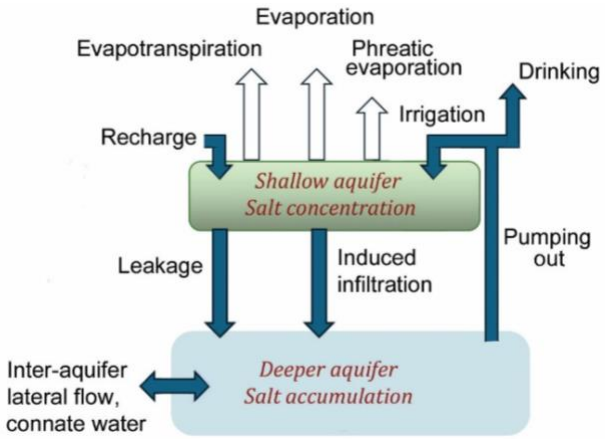


Figure 1. *Processes leading to groundwater salinization in an agricultural inland basin.*

regional changes in surface salinity patterns, e.g., soil (Wu et al., 2008).

3 Salinization in inland basins

Salt contamination has reached critical levels in many regions of North Africa, the Middle East, and Central Asia (OECD, 2001; Gurmessa et al., 2022; Li et al., 2025). The regions with the highest groundwater salinities are mainly aquifers that flow through soluble rocks such as limestone and evaporites (rock salt, gypsum) and occur in regions with very low precipitation. Regions with extensive agriculture experience human-induced groundwater salinization (MacDonald et al., 2016; Mateo-Sagasta and Albers, 2018). Many arid and semi-arid regions host large-scale agricultural operations, particularly in areas supported by irrigation (OECD, 2001; Mateo-Sagasta and Albers, 2018; Gutiérrez et al., 2021). Under unsustainable water management practices, increased salinization threatens not only the well-being of the population but also food security and may even result in forced human migration (van Deelen, 2024).

Since groundwater salinity varies widely in space and time, studies seek to determine the best methods to measure and classify its hazardousness by using quality indices, salinity diagrams, and other types of data manipulation. These are mostly based on water quality parameters like total dissolved solids (TDS), sodium (Na^+), calcium (Ca^{2+}) and magnesium (Mg^{2+}) (Hakami et al., 2024). Selected studies reporting salinization of inland basins are compiled in **Table 1** and discussed in the following sections.

3.1 Americas

In the U.S. Southwest and northern Mexico, intensive irrigation is a major contributor of salinization. Anning (2011) reports that 44% of groundwater solutes originate from dissolution of rocks and the remaining 56% from irrigation within the U.S. Southwest. In northern Mexico, multiple studies are dedicated to salinity (**Table 1**). For instance, in the Region Carbonífera, 76% of wells are unsuitable for irrigation due to high salinity and sulfate levels (Batista-Cruz et al., 2022), whereas Chihuahua and the Comarca Lagunera, studies link salinity to evaporite dissolution, aquifer depth, and irrigation returns from agricultural practices (Mendieta-Mendoza et al., 2020; Mora et al., 2021). In Central Mexico, shallow groundwater is saturated with minerals such as natronite and nontronite (**Table 1**), which adversely affect soil quality (Morán-Ramírez et al., 2024). In Brazil's Ceará region, salinity is attributed to meteoric inputs and high evapotranspiration, while in Argentina's Pampean plain, water evolves from fresh to highly saline due to lithology and residence time (Becher-Quinodóz et al., 2019; Kreis et al., 2024).

3.2 MENA region (Middle East and North Africa)

Studies from Morocco, Tunisia, and Algeria consistently report salinity being linked to evaporite dissolution and lithological factors (**Table 1**). For example, in Tunisia's Tabeditt aquifer, expanding irrigation exacerbated salinity. Ltifi et al. (2024) found three zones of salinities (as TDS) within the aquifer: 288–3,288 mg/L, 3,288–6,288 mg/L, and >6,288 mg/L TDS, and identified a main factor of salinization to be the return of concentrated (by evaporation) surface irrigation water. In Algeria, declining recharge and anthropogenic influences are listed as main salinity contributors (Aouati et al., 2023; Bourmada et al., 2024). In Egypt's El Minya Governorate, salinity levels reach up to 3,199 mg/L (**Table 1**), with mixing freshwater proposed as a mitigation strategy (Asmoay, 2023). In Jordan, the Amman Zarqa basin showed high variability in salinity and nitrate (**Table 1**), much higher (average 2,577 mg/L) in shallow aquifers under irrigated land (Salahat et al., 2014).

3.3 Other regions

In Yemen, a significant portion of the groundwater samples are unfit for irrigation due to high sodium, magnesium, and chloride levels (**Table 1**; Hakami et al., 2024). The salinity of the Afghanistan's Kabul Province relates to both natural evaporitic deposits and urban flows (**Table 1**; Zaryab et al., 2021). Interestingly, in Southern Iraq, 76% of wells are deemed suitable for irrigation (**Table 1**), suggesting relatively better groundwater quality (Al Maliki et al., 2024). In Pakistan's Punjab province, urbanization has led to increasing nitrate levels over time (**Table 1**), although some improvement was noted post-2015 (Ullah et al., 2024).

In India, the Mewat District reports extremely high TDS levels (up to 35,000 mg/L) due to rock-water interactions and high evaporation rates, while in South India, groundwater is generally suitable for irrigation but not for drinking due to elevated nitrate and fluoride (F^-) (**Table 1**; Krishan et al., 2017; Adimalla and Wu, 2019). In China's Ningxia Hui region, only 20% of wells are suitable for irrigation, with salinization driven by both natural and a mixture of anthropogenic factors, the latter resulting from long-term irrigation. Stagnant water bodies have slowed down the groundwater flow, increasing salinity (**Table 1**; Zhang et al., 2023). Lastly, in Ghana's Pru Basin, nearly 20% of wells are affected (**Table 1**), with Na^+ and Cl^- originating from mixed sources (Sunkari et al., 2021).

Multiple studies have focused on the source of salinization, while fewer studies report seasonal variation or salinity trends. With respect to salinity upward trends, the commonly scarce and fragmented water quality data for most regions restricts the statistical determination of these trends. In some studies, the concentrations have been collected over a few (2–5) years to determine the change of salinity with respect to time (Zaryab et al., 2021; Aouati et al., 2023; Espino-Valdés et al., 2024; Ullah et al., 2024), while other studies utilize large databases (8 to10 consecutive years for each season as a minimum). The latter is required to be used by more formal statistical methods, e.g., WRTDS or Mann-Kendall trend analysis (Hirsch et al., 2010; Harkness et al., 2023) to accurately determine salinization trends.

The reported main sources of groundwater salinity for inland basins include, in the order of importance, the dissolution of evaporite and carbonate rocks, mixing of groundwater with saline groundwater and/or surface water, evaporation, and meteoric deposition (Li et al., 2020; Yang et al., 2022). In agricultural land, the infiltration of water

Table 1. *Selected studies reporting groundwater salinity of arid and semiarid inland basins.*

Country, Region	Methods*	Highlights of findings	Reference
Americas			
Northern Mexico, Region Carbonífera	1-7	76% of wells impaired for irrigation due to high salinity, excess sulfate.	Batista-Cruz et al. (2022)
North-central Mexico	1, 2, 3, 9, 10	The study area is divided into three regions by climate. Upward trends found in 6 out of 59 aquifers; only one aquifer affected severely.	Colmenero-Chacón et al. (2023)
Northern Mexico, Chihuahua	1, 3, 8, 9	Irrigated agriculture, salinity tied to dissolution of evaporites high in sulfate.	Mendieta-Mendoza et al. (2020)
Northern Mexico, Comarca Lagunera	1, 2, 7, 9	Salinity is linked to aquifer depth, contact with saline aquitards, and evaporation. In agricultural areas also to groundwater abstraction and irrigation returns.	Mora et al. (2021)
Central Mexico, Tierra Nueva aquifer	1-2, 4-6	Shallow groundwater (5 m depth) saturated with natronite and Na, Ca, K nontronite, affecting irrigated soils	Morán-Ramírez et al. (2024)
Northeastern Brazil, Ceará region	1, 2, 7, 9	Salinity (Cl) traced to meteoric inputs and high evapotranspiration rate.	Kreis et al. (2024)
Argentina, Pampean plain aquifer	1, 2	Water evolves from fresh (recharge area) to high TSD (3,093 mg/L). Salinity related to lithology and residence time.	Becher-Quinodóz et al. (2019)
MENA Region (Middle East and North Africa)			
Southeast Morocco, Zagora graben	1, 2, 5, 7, 8	Groundwater with low pH and EC up to 5 mS/cm. Salinity related to lithology, e.g., dissolution of carbonates and Ca-silicates.	Ait Lemkademe et al. (2023)
Southern Tunisia, Tabeditt region	1, 2, 5, 6, 11	Evaporite dissolution is the main source of salinity, aggravated by expansion of irrigated agriculture.	Ltifi et al. (2024)
Northeast Algeria, Ain Azel Plain	1, 3, 5	Decline in groundwater recharge since 2013, deterioration of groundwater quality.	Aouati et al. (2023)
Northeastern Algeria, Souk Ahras region	1-3, 5, 6, 8	High salinity related to natural (dissolution of evaporites) and anthropogenic sources. Most water suitable for human consumption, but Mg severely limits its use for irrigation.	Bourmada et al. (2024)
Central Egypt, El Minya Governorate	1-3, 6, 8-9	High salinity (up to 3,199 mg/L) caused by dissolution of evaporites. Mixing with freshwater an option to improve quality.	Asmoay (2023)
Jordan, Amman Zarqa basin	2-3, 8	Huge variability of salinity and nitrate across the study area. Highest salinity in shallow aquifers under irrigated land.	Salahat et al. (2014)

Table continued to next page.

Others			
Yemen, Taiz Governorate	1-4	69% of samples are unfit for irrigation using Na and salinity, and Mg for 55% of samples. High Cl content, some wells exceeding 350 mg/L.	Hakami et al. (2024)
Afghanistan, Kabul Province	1-3, 5, 8-10	Salinity is linked to dissolution of evaporitic lacustrine deposits and urban flows.	Zaryab et al. (2021)
Southern Iraq, Mesopotamian Plain	1-9	76% of wells fit for irrigation purposes (Wilcox)	Al Maliki et al. (2024)
Pakistan, Punjab province	1-3	Groundwater impacted by urbanization, evident by increasing nitrate with time (sampled 2010, 2015, 2021) but improved in two regions in after 2015	Ullah et al. (2024)
Northern India, Mewat District	1-2, 5-6	Rainfed agriculture, TDS reaching 35,000 mg/L in some locations. Source of salinity listed as rock-water interaction	Krishan et al. (2017)
South India, Siddipeta-Vagu region	1-6	Groundwater dominant type Na-HCO_3, fit for irrigation but some wells unfit for drinking due to high nitrate and fluoride.	Adimalla and Wu (2019)
China, Ningxia Hui region	1-8	Salinization from both natural and human factors, with 20% of the wells suitable for irrigation.	Zhang et al. (2023)
Middle belt of Ghana, Pru Basin	1-3, 5, 7, 8	19.8% of the wells were affected. Major ions Na and Cl from both geogenic, anthropogenic sources.	Sunkari et al. (2021)

*Note: *Methods: 1. Major ions, 2. TDS, 3. Salinity indices, 4. Salinity diagrams, 5. Piper diagram, 6. Gibbs diagram, 7. Stable isotopes, 8. Multivariate statistics, 9. Correlation, 10. Trend, 11. Electrical resistivity tomography.*

containing irrigation returns becomes an important additional contributor of groundwater salinity (Pulido-Bosh et al., 2018; Foster et al., 2018). Approximately 80% of the irrigated land worldwide is found in semiarid areas, and many of them are in developing countries (Morris et al., 2003; Mateo-Sagasta and Albers, 2018). Changes in land use and land cover, such as urbanization and changing the natural cover to agricultural cover, can also impact salinity by the additional input of salt-laden wastes (Scanlon et al., 2007; Zaryab et al., 2021; Ullah et al., 2024).

4 Methods utilized in salinization studies

Studies commonly report one or more of the following parameters to determine the amount of salinity: major ions, TDS, salinity indices, electrical conductivity, and salinity diagrams (Ltifi et al., 2024), whereas the evolution of salinity relies on Piper diagram, Gibbs diagram, stable isotopes, multivariate statistics, or trend analyses. Newer methods that have been applied to salinization include machine learning (Gharechaee et al., 2024; Sarkar et al., 2024) and mathematical modeling (Cao et al., 2024). Geophysical methods (electrical resistivity, time-domain electromagnetics) have the potential to determine subsurface electrical resistivity variations and apply them to groundwater salinization (Yang et al., 2022); to depths up to 100–200 m. Conventional methods used to study groundwater salinization are summarized below. For simplicity purposes, the formulas of the quality indices, statistical manipulations, and water quality diagrams are not included here, but can be found in the references therein.

4.1 Major ions

Most groundwater salinity studies report the concentration of major ions Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, HCO_3^{-}, Cl^{-}, and SO_4^{2-}, TDS, whereas some studies also report other toxic contaminants such as F^{-}, As, Se, and U (Krishan et al., 2017; Li et al., 2020). The contribution of human activities (anthropogenic contaminants) commonly relies on an indicator parameter such as the soluble salt nitrate (Salahat et al., 2014). The origin of the nitrate has been associated with several sources including animal waste, sewage, and excess synthetic fertilizer, and it is found to have gradually increased in world aquifers to a point that is now considered one of the most widely spread contaminants (Puckett et al., 2011). Other parameters, such as chloride concentrations and TDS, may be used in conjunction with nitrate concentrations to detect the presence of anthropogenic contamination (Salahat et al., 2014; Zaryab et al., 2021; Espino-Valdés et al., 2024).

4.2 Total dissolved solids

Total dissolved solids (TDS, in mg/L) is a parameter directly related to salinity and can be used as a quantification of salinity (Salahat et al., 2014; Gurmessa et al., 2022). TDS is usually determined using electrical conductivity (EC) measurements, by adding the concentrations of major ions, or as a direct measurement obtained after evaporating a known volume of water (Salahat et al., 2014). TDS values are reported in most studies, and some studies base their salinity analyses in TDS alone (Brito-Almeida et al., 2024). Besides being a powerful measurement by itself, TDS may be combined with other parameters (e.g., Cl^-, HCO_3^-) to form ratios, indices, and diagrams that have the main purpose of enhancing the evidence and the source of salinity.

4.3 Salinity indices

There are a wide variety of salinity and water quality indices. Some of the most commonly used indices include the sodium absorption ratio (SAR), percent sodium (Na%), soluble sodium percentage (SSP), magnesium hazard ratio (MHR), Kelly Ratio (KH), water quality index (WQI) and nitrate pollution index (NPI) (Ortiz-Letechipia et al., 2021; Hakami et al., 2024; Ullah et al., 2024). Water quality indices provide an easy method to visualize potentially harmful compositions by combining a few parameters into one resulting number that is attached to a category, e.g., low, moderate, or high contamination (**Table 1**).

4.4 Salinity diagrams

Salinity diagrams such as Wilcox and USSL are widely used to evaluate the suitability of groundwater for irrigation. In the Wilcox diagram, Na% is plotted against EC, categorizing water quality based on salinity and sodium-related hazards (Wilcox, 1955). The USSL diagram provides a more detailed analysis by plotting the sodium adsorption ratio (SAR) against EC. It classifies water into salinity (C1–C4) and sodium hazard (S1–S4) categories.

4.5 Piper diagram

The trilinear Piper diagram (Piper, 1944), a common addition to groundwater studies, is used to determine the dominant anion and cation, information that translates into the water type, e.g., Ca-HCO_3 or Na-Cl, etc. When groundwater samples are plotted on this diagram, they reveal patterns that can indicate whether the water is fresh, saline, or influenced by specific geochemical processes like ion exchange or mixing. For example, groundwater that plots in the sodium-chloride zone of the diamond field is typically more saline and may be influenced by seawater intrusion or evaporite dissolution. On the other hand, water that falls in the calcium-bicarbonate zone is often fresh and associated with recharge areas. This makes the Piper diagram particularly useful for comparing multiple water samples across a region and identifying shifts in water chemistry due to natural or anthropogenic factors.

4.6 Gibbs diagram

The Gibbs diagram (Gibbs, 1970) plays a valuable role in understanding the salinity of groundwater by helping to identify the dominant processes that control its chemical composition. It is a simple yet powerful graphical tool that plots the ratio of major ions; typically, Na^+, K^+, Cl^-, and HCO_3^- against TDS. This allows easy interpretation of whether the salinity in groundwater is primarily influenced by precipitation, rock-water interaction, or evaporation-crystallization processes.

4.7 Stable isotopes

Stable isotope analyses δ^2H, $\delta^{18}O$, $\delta^{13}C$, and $\delta^{15}N$, are powerful tools in hydrogeological investigations (Qu et al., 2024). These isotopes help determine the origin, age, and movement of groundwater, as well as identify recharge zones and distinguishing between local and regional flow systems. For instance, plotting chloride concentrations against $\delta^{18}O$ values can differentiate between phreatic evaporation and salt fractionation processes, which are key mechanisms in groundwater salinization (Batista-Cruz et al., 2022). Moreover, isotopes such as $\delta^{15}N$ and $\delta^{13}C$ can be used to trace the sources of dissolved solutes, particularly nitrogen species like nitrate (NO_3^-). $\delta^{15}N$ values can help distinguish between nitrate derived from synthetic fertilizers and that originating from organic sources such as manure or sewage (Ortiz-Letepichia et al., 2021). This is crucial in assessing anthropogenic contributions to groundwater contamination, especially in agricultural and peri-urban settings. Values of δ^2H and $\delta^{18}O$ are commonly used to identify evaporative enrichment, a hallmark of salinization in arid and semi-arid regions (Qu et al., 2024). Elevated $\delta^{18}O$ values are often correlated with increased salinity, indicating that water has undergone significant evaporation before or during infiltration. Additionally, $\delta^{34}S$ and $\delta^{18}O$ in sulfate can reveal whether salinity arises from evaporite dissolution or industrial discharges.

4.8 Multivariate statistics

Multivariate computer-based methods, such as Principal Component Analysis (PCA) and Hierarchical Cluster Analysis (HCA) group water quality parameters based on statistical similarities, allowing researchers to identify patterns and associations that may not be evident through conventional analysis (Sunkari et al., 2021). These methods are particularly effective in detecting groundwater salinization, isolate the influence of key ions such as Na^+, Cl^-, and SO_4^{2-}, and distinguish between natural and anthropogenic sources. When integrated with spatial analysis techniques, these multivariate approaches enable the mapping of salinity patterns and the identification of hotspots where salinization processes are most active (Salahat et al., 2014; Mora et al., 2021).

4.9 Correlation

A correlation analysis of chemical parameters is a fundamental approach in hydrogeochemistry for identifying relationships among solutes and inferring their sources. By examining how different ions co-vary across groundwater samples, researchers can determine which solutes likely originate from the same geochemical process or source rock. The non-parametric Spearman rank correlation is commonly employed. Unlike Pearson's correlation, Spearman's method does not assume linearity or normality, making it more robust for analyzing skewed or ordinal data typical in groundwater studies. In the context of groundwater salinization, correlation analysis helps to distinguish between natural and anthropogenic sources of salinity. For instance, a correlation between nitrate and chloride may point to agricultural runoff or sewage contamination, whereas a lack of correlation between salinity and depth might suggest surface-driven processes like evaporation or irrigation return flows (Fosu et al., 2025).

4.10 Salinity trends

Trends can be determined by various methods. Commonly used techniques include both statistical and spatial analyses, such as Mann-Kendall trend analysis (Mann, 1945) and weighted regressions on time, discharge, and season (WRTDS) (Hirsch et al., 2010), respectively. Each of these methods requires a minimum number of consecutive measurements (about 10 for Mann-Kendall, 200 for WRTDS) for optimal performance.

4.11 Electrical resistivity tomography

Electrical resistivity tomography is a non-destructive surface geophysical method to determine subsurface electrical resistivity variations usually along two-dimensional profiles that can be used to characterize the path of groundwater and to interpret salinization (Asfahani, 2011; Adhikary et al., 2015). The method inserts electrical current via electrodes spaced at specific intervals into the ground and electrical voltage potentials are determined between the electrodes using a specific electrode configuration or array (Ltifi et al., 2024). The data are commonly modeled using two-dimensional inversion methods and the electrode spacing and array length will determine the maximum depth that can be imaged, usually is less than 100 meters. While two-dimensional profiles are the most used measuring methods, three-dimensional surveys are becoming more common (Loke et al., 2020).

5 Results and discussion

5.1 Groundwater salinity

Table 2 lists concentrations of the salinity parameters TDS and Na^+, and the anthropogenic soluble ion NO_3-N reported for salinity affected regions. This list offers a quick visualization of the range of the values encountered in regions where groundwater is becoming or is already saline and their geographic locations. Several studies have reported ions that pose a concern for groundwater quality in specific regions (Li et al., 2020), including trace elements such as F^- (Krishan et al., 2017; Adimalla and Wu, 2019), boron (Al Maliki et al., 2024), arsenic (As) (Mora et al., 2021; Ortiz-Letechipia et al., 2021), vanadium and uranium (Mora et al., 2021) or major ions present at exceptionally high concentrations, including sodium (Al Maliki et al., 2024), magnesium (Bourmada et al., 2024), chloride (Aouati et al., 2023; Asmoay, 2023; Kreis et al., 2024; Hakami et al., 2024) or sulfate (Batista-Cruz et al., 2022; Al-Maliki et al., 2024).

One parameter that has increased in importance in the last few decades is nitrate (either as NO_3^- or NO_3-N), whose concentrations have rapidly increased in aquifers worldwide and is associated with human induced salinity and/or intensive agriculture (Puckett et al., 2011). As a result, it is now commonly included in salinity studies (Salahat et al., 2014; Li et al., 2020). The highest concentrations are reported in irrigated regions as it is present in inflows carrying excess of synthetic N-fertilizers, manure, and/or sewage (Foster et al., 2018; Pulido-Bosch et al., 2018).

Based on the values of salinity and Na^+ content, salinity problems seem more acute in dry areas of the Middle East and north African countries, where evaporation rates are high (**Table 2** and **Figure 2**). Within a particular region, salinity increases at the lowest elevation points in the valleys and with residence time, as expected due to a longer passage of groundwater through rocks, and in some cases becoming in contact with a salt crust or a sebkha (salt shallow lake) typical of arid areas, (Mora et al., 2021; Aouati et al., 2023).

High spatial and seasonal variations of salinity concentrations are typical for semiarid and arid areas (Kreis et al., 2024; Al Maliki et al., 2024). Seasonal variations must be accounted for when determining salinity trends, and its identification requires a larger number of monitoring data in terms of years data collected and stations. High spatial variabilities of salinity are common, which in many instances reflect the heterogeneous nature of the aquifer, such as clay lenses and caliche layers in alluvial unconfined aquifers (Mora et al., 2021). Also, land use may affect the water quality of certain areas within the aquifer more than other areas (Salahat et al., 2014; Ullah et al., 2024). With respect to the upward trend in salinity concentrations worldwide, some regions report either an increasing groundwater salinity (MacDonald et al., 2016) or no trend (Bouimouass et al., 2022). In some inland basins, salinity increase has been slow, as in north-central Mexico, where upward trends were reported for a merely 5% of the tested aquifers (Colmenero-Chacón et al., 2023).

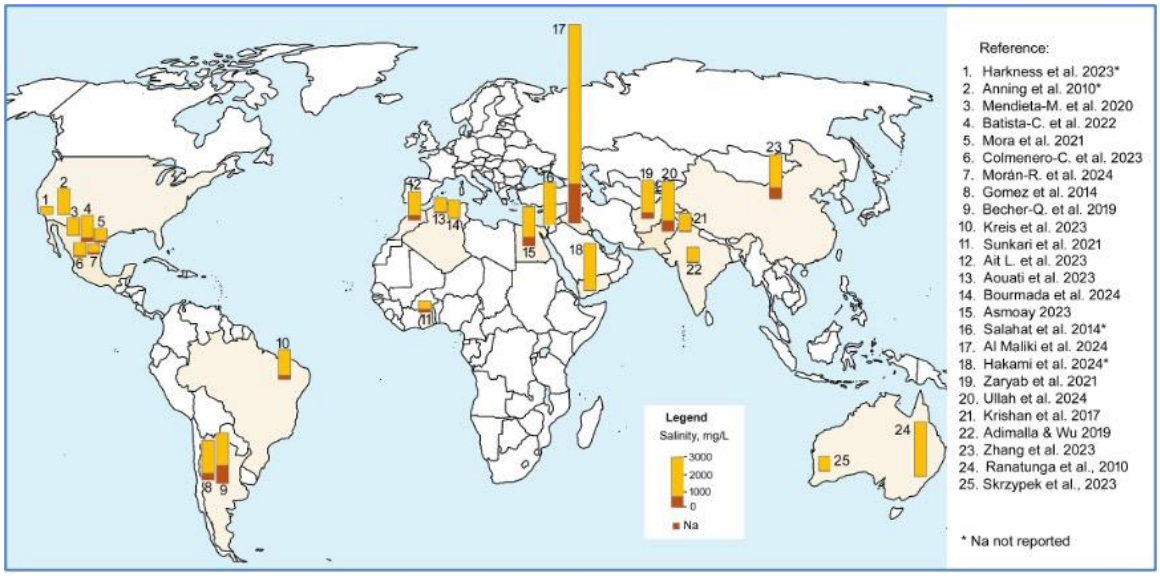
5.2 Social aspects and recommendations for sustainable use

As highlighted by the studies discussed above, the quality of groundwater, the primary water source in arid and semi-arid regions is increasingly at risk (OECD, 2001; Etikala et al.,

Table 2. *Average salinity values (as TDS), Na^+, and NO_3-N for selected regions (N = Number of wells, n.r.= not reported).*

Region	N	TDS (mg/L)	Na (mg/L)	NO_3-N (mg/L)	Reference
Americas					
Northern Mexico	83	1,639 deep 1,211 shallow	276 136	n.r.	Batista-Cruz et al. (2022)
Northern Mexico	30	1,095	53	1.7	Mendieta-Mendoza et al. (2020)
Northern Mexico	55	884	150	12.3	Mora et al. (2021)
Central Mexico	98 94 33	349 mountain 678 transition 924 plain	72 117 141	2.0 5.6 10.0	Colmenero-Chacón et al. (2023)
Central Mexico	19	648	161	1.5	Morán-Ramírez et al. (2024)
Argentina	90	3,093	1,135	n.r.	Becher-Quinodóz et al. (2019)
Northeast Brazil	38	1,824	275	16.1	Kreis et al. (2024)
MENA Region					
Southeast Morocco,	17	1,762	321	1.2	Ait Lemkademe et al. (2023)
Southern Tunisia	30 7 3	1,233 western 4,197 central 7,856 eastern	21 22 23	n.r. n.r. n.r.	Ltifi et al. (2024)
Northeast Algeria,	20 18 15 39	925 (2002) 928 (2008) 947 (2017) 961 (2018)	75 94 84 96	n.r.	Aouati et al. (2023)
Northeastern Algeria	22	1,099 rainy 1,158 dry	55 61	1.0 1.0	Bourmada et al. (2024)
Central Egypt	33	2,402	563	n.r.	Asmoay (2023)
Jordan	178	2,577 irrigated 745 rainfed 672 natural	n.r.	19.6 6.4 5.9	Salahat et al. (2014)
Other regions					
Yemen	29	2,903	51	n.r.	Hakami et al. (2024)
Afghanistan	41	1,425 (2004) 2,342 (2021)	230 390	6.9 5.1	Zaryab et al. (2021)
Southern Iraq	57	12,012	2,399	11.3	Al Maliki et al. (2024)
Pakistan, Punjab province	24	1,041 (2010) 2,933 (2015) 3,049 (2021)	285 825 687	2.2 8.0 7.2	Ullah et al. (2024)
Northern India	21	1,163	123	10.5	Krishan et al. (2017)
Southern India	51	985	93	17.4	Adimalla and Wu (2019)
China, Ningxia Hui region	62	1,450	285	n.r.	Zhang et al. (2023)
Ghana, Pru Basin	81	717	226	1.0	Sunkari et al. (2021)

2021). The groundwater conditions in developing countries are further challenged by low budgets and lack of infrastructure. For example, surface water is commonly stored in open reservoirs that are subjected to a high evaporation rate, and managed aquifer recharge plans have been seldom implemented beyond pilot scale (Gutiérrez et al., 2021; Taucare et al., 2024). Developing strategies to address water sustainability and water resilience is a critical and urgent task based on the above problems (Scanlon et al., 2021; Yang et al., 2022; Taucare et al., 2024).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6. Colmenero-C. et al. 2023
7. Morán-R. et al. 2024
8. Gomez et al. 2014
9. Becher-Q. et al. 2019
10. Kreis et al. 2023
11. Sunkari et al. 2021
12. Ait L. et al. 2023
13. Aouati et al. 2023
14. Bourmada et al. 2024
15. Asmoay 2023
16. Salahat et al. 2014*
17. Al Maliki et al. 2024
18. Hakami et al. 2024*
19. Zaryab et al. 2021
20. Ullah et al. 2024
21. Krishan et al. 2017
22. Adimalla & Wu 2019
23. Zhang et al. 2023
24. Ranatunga et al., 2010
25. Skrzypek et al., 2023
* Na not reported
Legend
Salinity, mg/L
3000
2000
1000
0
Na

Figure 2. *Groundwater salinity (as TDS and Na^+) reported for semiarid inland basins.*

Morris et al. (2003) lists five recommendations for effective management of an aquifer. Briefly, these are: (a) awareness of the status of groundwater quality and amount, (b) understanding the nature of the aquifer, (c) have water laws in place, (d) monitor adherence to regulatory measures, and (e) awareness of the importance of groundwater. In the case of salinity, measures rely on conjunctively managing surface water and groundwater. To mitigate the degradation of groundwater quality, several recommendations have been proposed, including the development and implementation of regulatory frameworks and sustainability indicators (OECD, 2001; Perez et al., 2015). A practical solution consists of mixing saline water with freshwater to achieve compliance with drinking water regulations (Asmoay, 2023; Hakami et al., 2024); where freshwater could be obtained from rainwater harvesting or solar desalination.

Methods for managing groundwater in agricultural areas include adopting irrigation techniques that reduce the use of water and maintain the soil salinity at low levels. The former includes drip irrigation and the latter maintaining the soil as well-drained as possible and washing soil excess salts with freshwater (Hakami et al., 2024). An important component of managing groundwater salinity is the selection of crops. An effective use of scarce water has been the cultivation of salt-tolerant crops, e.g., barley, sorghum, alfalfa, and quinoa (Hakami et al., 2024), taking care that the crops are not only resistant to saline conditions, but also do not accumulate toxic elements such as As or Pb in their edible parts (Ochoa-Rivero et al., 2023). A rule of thumb is to continue long-time traditional agricultural practices if these have successfully maintained groundwater levels and quality (Bouimouass et al., 2022). Available data (chemical, meteorological, borehole) can be used to model trends in all the parameters and scenarios under various management practices and climatic conditions (Cao et al., 2024; Hamed et al., 2024). Technologies such as GIS and machine learning to identify the most vulnerable areas (Hakami et al., 2024). Protection of natural aquifer recharge areas is essential, as is land use and land cover management of croplands potentially affected by salinity (Yan et al., 2022).

Unusual strategies include using saline water in aquaculture to grow carp (Nagaraja et al., 2025), desalinating irrigation water (Khedher et al., 2025) and managing groundwater levels in irrigated land (Zhang et al., 2024). An integrated water management that involves communities and stakeholders is critical to develop policies to regulate groundwater abstraction (Morris et al., 2003; Perez et al., 2015). This includes education and awareness-raising, sensitizing local communities on feasible sustainable agricultural practices and the effects of using contaminated water (Morris et al., 2003; Hakami et al., 2024). The protection of groundwater resources also requires adequate policy implementation and enforcement, among other systemic constraints. Two examples below, one region in Mexico and the other in Ghana, illustrate the standing and particularities with respect to groundwater salinization.

6 Case study: Northern Mexico

A semiarid irrigate area in northern Mexico (Irrigation district 005), has groundwater naturally contaminated with F^- and As (Gutiérrez et al., 2021; Padilla-Reyes et al 2024). Two rivers, Conchos and San Pedro, provide water to the region. The rivers' streamflow has greatly diminished in the last few decades (Scanlon et al., 2007). With less surface water available for irrigation, farmers resort to groundwater to complement the water required by the crops, especially during dry years (Gutiérrez et al., 2021). The Meoqui-Delicias aquifer, an unconfined alluvial aquifer with an average thickness of 300 m, supplies the water needed (**Figure 3**). The aquifer is recharged at the alluvial fans that border the plains, and the groundwater is discharged at stream. In the irrigated area, a significant amount of irrigation water seeps back to the aquifer, a process that promotes the

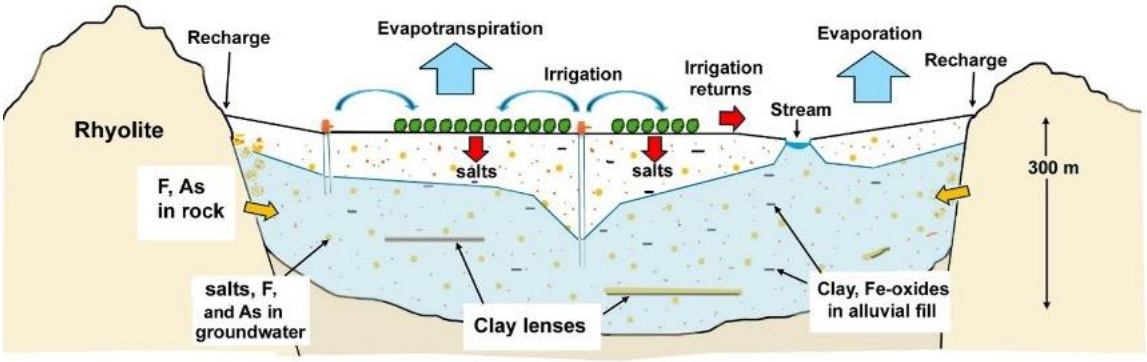

Figure 3. *Schematic representation of processes causing salinity in the unconfined aquifer under the irrigation district DR005 in northern Mexico.*

infiltration of surface contaminants, as indicated by the presence of NO_3-N in deep wells (Espino-Valdés et al., 2024). Groundwater salinity (TDS) and NO_3-N had an average of 853 mg/L and 7.5 mg/L, respectively, based on 53 groundwater samples collected throughout the DR005 in 2021 (Espino-Valdés et al., 2024).

Groundwater monitoring is key to finding potential strategies to prevent the infiltration of contaminants and the further decline of water levels. In an effort to determine variations in groundwater salinity, water quality data (TDS, major ions, and As) for 14 wells and five stream sites reported by the Mexican Water Office (CONAGUA, 2024a) for 2014-2020 were analyzed. The water quality data were grouped into three regions and further categorized by season. The results are shown in **Table 3**. The two seasons are defined as dry (October to June) and wet (July to September).

As seen in **Table 3**, a large standard deviation was obtained for each parameter. A closer look at the data revealed a large variation in location and less with respect to time or season. At the confluence of the two rivers, located downstream of the irrigation district, the salinity had an intermediate value instead of increasing further. Major ions followed this pattern, but NO_3-N, As, and SAR did not. The

Table 3. *Water quality of wells adjacent to the rivers Conchos, San Pedro, and at their confluence. Samples were collected between 2014 and 2020 (CONAGUA, 2024a); Ndry = Number of samples collected in the dry season, and Nwet = Number of samples collected in the wet season.*

Parameter	Season	Conchos River 4 wells Ndry = 16 Nwet = 6	San Pedro River 4 wells Ndry = 9 Nwet =6	Confluence 6 wells Ndry = 22 Nwet = 9
TDS, mg/L	Dry Wet	1,418 ± 428 1,279 ± 388	571 ± 177 545 ± 187	753 ± 329 861 ± 321
Na^+, mg/L	Dry Wet	268 ± 123 272 ± 88	116 ± 63 110 ± 43	173 ± 83 193 ± 70
Cl^-, mg/L	Dry Wet	119 ± 86 106 ± 93	26 ± 16 26 ± 16	45 ± 28 70 ± 45
SO_4^{2-}, mg/L	Dry Wet	578 ± 229 591 ± 300	163 ± 103 163 ± 110	238 ±195 325 ± 206
Hardness, mg/L $CaCO_3$	Dry Wet	416 ± 155 371 ± 168	217 ± 60 161 ± 64	243 ± 104 271 ± 111
NO_3-N, mg/L	Dry Wet	6.3 ± 3.4 3.4 ± 3.6	5.0 ± 3.0 3.7 ± 2.7	4.4 ±2.2 4.4 ± 2.5
As, mg/L	Dry Wet	0.054 ± 0.052 0.084 ±0.058	0.030 ± 0.010 0.025 ± 0.010	0.134 ± 0.192 0.120 ± 0.128
Sodium absorption ratio (SAR)	Dry Wet	5.7 ± 2.2 6.5 ± 2.1	3.4 ± 1.8 3.9 ± 1.3	6.2 ± 5.5 7.0 ± 6.0

average NO_3-N concentrations were equally dispersed throughout the area, with a little seasonal effect. Conversely, As increased significantly at the discharge near the confluence, a behavior likely related to groundwater reaching San Diego de Alcala, an area rich in clay deposits with naturally high As content (CONAGUA, 2024b). One of the wells from the area of confluence had consistently SAR values above ten, signaling water unfit for irrigation. Despite this being one out of 14 wells studied, it is an indication that the groundwater is reaching a critical point with respect to salinity. The detection of relatively high NO_3-N values in deep parts of the aquifer is also concerning, as it evidences the infiltration of surface contaminants.

The results further suggest a close interaction between surface water and groundwater, moderate salinity that decreases near the San Pedro River (**Table 4**). NO_3-N, concentrations in groundwater are higher than in the nearby surface water, indicating a NO_3-N accumulation more than 2-fold compared to the surface waters. Arsenic concentrations in groundwater are also more than 2-fold those of surface water, but this is an expected result considering that As is a weathering product of the alluvial fill material. Basic recommendations to add sustainability to the groundwater quality of the area include (a) implementing water-efficient techniques such as drip irrigation, (b) restrict the use of N-fertilizers to only the amount needed by the crop, (c) grow water efficient crops such as cotton, groundnuts, and barley, and (c) reduce as much evaporation as possible in water storage facilities and irrigation canals.

7 Case study: Pru Basin, Ghana

The semiarid Pru Basin covers almost entirely, the whole of the Bono East Region of Ghana, where agriculture and fishing are the primary occupations. The area is famously recognized as the nation's food hub, leading to the migration of farmers from the north and the two upper regions of Ghana. Serving as Ghana's food basket, commercial agriculture in this area incorporates the application of herbicides, fertilizers, and various farming inputs. This part of Ghana is marked by a notably thick regolith profile because of the dominant climatic conditions in the area that promote more intense chemical weathering (Sunkari et al., 2021). The dominance of farming practices in and near the semiarid Pru Basin, along with its substantial regolith layer, tends to affect groundwater chemistry through infiltration from agricultural areas and waste from increasing agrochemical retailers in the basin's catchment, while also considering the impact of natural geogenic sources. Ultimately, the quality of the water would be compromised, significantly affecting the health and well-being of those living in rural areas. Additionally, every river in the semiarid Pru Basin is included in the Volta River drainage system, acting as tributaries to the Volta Lake. Following these possible risks to groundwater quality in the region, limited data exists regarding the current state of groundwater chemistry, making it difficult to monitor and develop effective management practices for the semiarid Pru Basin catchment, which is not thoroughly covered in existing literature. The processes influencing groundwater chemistry in the semiarid Pru Basin remain inadequately comprehended. Sunkari et al. (2021) conducted a thorough hydrogeochemical study in the basin and reported higher levels of groundwater salinity in about 81 hand-dug wells and boreholes. The study indicated that the EC values in groundwater in the semi-arid Pru Basin vary between 306 and 7,914 µS/cm, averaging at 797 µS/cm (**Table 5**), indicating a lack of compliance with the World Health Organization's (WHO) guideline value of 1,000 µS/cm (WHO, 2022). The high values result from a prolonged residence time of groundwater within the aquifer (Karunanidhi et al., 2021).

Concentrations of TDS in groundwater within the semiarid Pru Basin range from 275 to 7,123 mg/L, with an average of 717 mg/L (**Table 5**; Sunkari et al., 2021), surpassing the WHO's guideline of 1000 mg/L (WHO, 2022). These TDS levels compare to those reported by Egbi et al. (2019) for the Lower Volta River Basin and Tay (2012) for the Middle Volta River Basin.

The dominant cation was Na^+, with concentrations ranging from 25.2 to 2,115 mg/L, with a mean value of 226 mg/L. Out of 26 samples (4 from boreholes and 22 from hand-dug wells), approximately 32.1% of the total samples showed Na^+ concentrations above the guideline value. The elevated Na^+ levels are probably the result of ion exchange processes within the aquifer (Yidana et al., 2018). Among the anions, Cl^- exhibits the greatest concentrations, varying from 1.36 to 4,671 mg/L, with an average of 240 mg/L (**Table 5**; Sunkari et al., 2021). The elevated Cl^- concentrations might be attributed to ion exchange processes in the aquifer

Table 4. *Average of concentrations for surface water and groundwater in each of the studied regions (2014-2020 data).*

Regions	Sampling medium and No. of samples	TDS (mg/L)	NO_3-N (mg/L)	As (mg/L)
Conchos River, 4 sampled wells	Surface water, N = 20 Groundwater, N = 23	777 1,381	0.45 6.11	0.015 0.062
San Pedro River, 4 sampled wells	Surface water, N = 29 Groundwater, N = 14	554 561	2.01 4.50	0.017 0.028
Confluence, 6 sampled wells	Surface water, N = 36 Groundwater, N = 30	894 785	1.25 4.47	0.036 0.130

Table 5. *Summary statistical description of important hydrochemical parameters in the semiarid Pru Basin (Sunkari et al., 2021); Std. Dev. = standard deviation, n.d. = not detected).*

Parameter	No.	Minimum	Maximum	Average	Std. Dev.
EC, mg/L	81	306	7,914	797	933
TDS, mg/L	81	275	7,123	717	840
Na^+, mg/L	81	25.2	2,115	226	254
K^+, mg/L	81	0.98	10.8	2.00	1.4
Ca^{2+}, mg/L	81	8.16	505	48.2	61.6
Mg^{2+}, mg/L	81	0.24	84.8	18.8	12.3
Cl^-, mg/L	81	1.36	4,671	240	634
SO_4^{2-}, mg/L	81	0.01	72.6	13.2	16.4
HCO_3^-, mg/L	81	121	641	430	113
NO_3-N, mg/L	81	n.d.	19.7	1.2	3.3

system, aligning with the observed high TDS and EC values (Sunkari et al., 2019). NO_3-N levels are typically below the WHO guideline limit of 10 mg/L for all samples, except for one from a hand-dug well in Yeji Township, which reaches 19.7 mg/L (**Table 5**), likely due to human activities such as the use of agrochemicals (Zango et al., 2019).

Owing to significant recharge processes, the Piper diagram is deemed inefficient to depict groundwater evolution and hydrochemical facies (Giménez-Forcada, 2010; Fosu et al., 2025). Therefore, the Hydrochemical Facies Evolution Diagram (HFE-D) was utilized to further validate the findings of Sunkari et al. (2021). The HFE-D distinctly separates groundwater samples from the semiarid Pru Basin (**Figure 4**). In this basin, around 64.2% of the samples are in the freshening phase, while about 35.8% are in the intrusion phase. During the freshening and intrusion phases, five different hydrochemical facies were identified (**Figure 4**). The freshening phase includes Mg-HCO_3, Na-HCO_3, MixMg-HCO_3, MixNa-HCO_3, and Na-MixCl facies. The intrusion phase comprises Mg-Cl, Mg-HCO_3, Na-Cl, MixMg-Cl and MixNa-Cl facies. The mixed facies result from a negative hydraulic gradient in the aquifer). Groundwater samples with a mix (Na^+ + Mg^{2+} + Cl^-) type suggest salinization due to cation exchange, while those with Na^+ and Cl^- facies indicate inland saltwater intrusion in the semiarid Pru Basin. As salinity increases during the intrusion stage, several samples show that groundwater characteristics are influenced by reverse ion exchange involving Na^+ and Mg^{2+}. Overall, the HFE-D for the semiarid Pru Basin shows the evolution of groundwater from Na-HCO_3 to Na-Mg-HCO_3 water types, indicating the combined influence of natural processes and human activities on groundwater chemistry. This diagram highlights the complexity of groundwater salinization and the need for integrated management approaches to mitigate its impacts.

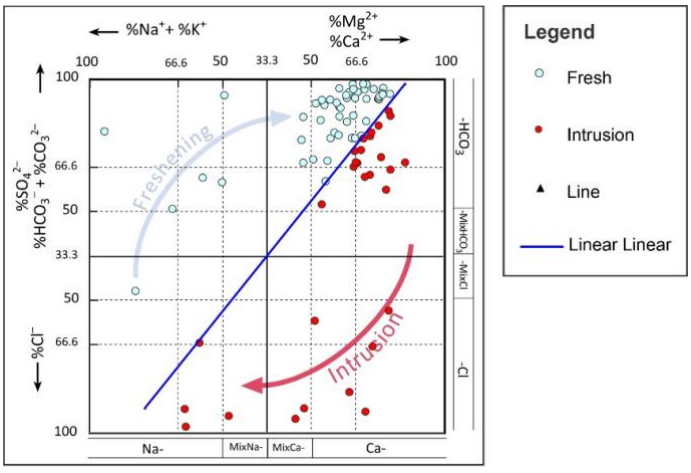

Figure 4. *Hydrochemical facies evolution diagram (HFE-D) for the semiarid Pru Basin in Ghana (data taken from Sunkari et al., 2021).*

Additionally, the Revelle Index is a crucial tool to assess the extent of salinity in groundwater, which is vital for understanding water quality and its suitability for various uses (Karunanidhi et al., 2021). By evaluating the ratio of chloride to bicarbonate and carbonate ions, the Revelle Index provides insights into the salinity levels and potential sources of contamination, aiding in the development of effective groundwater management and mitigation strategies. Sunkari et al. (2021) employed the Revelle Index to establish the degree of groundwater salinization in the semiarid Pru Basin. From their study, the calculated values of the Revelle index varied from 0.01 to 66.2, above the 0.5 threshold for salinization. Therefore, from the calculated Revelle Index values, evaluation of groundwater salinization in the semiarid Pru Basin shows that approximately 19.8% of groundwater samples with Revelle Index values greater than 0.5 are impacted by salinization. Groundwater salinization is more prevalent in the southwestern part of the basin. Consequently, to pinpoint the possible sources of groundwater salinization in the semi-arid Pru Basin, ionic ratio diagrams were employed by Sunkari et al. (2021). This approach revealed that groundwater salinization in the semiarid Pru Basin arises from a combination of factors including inland saline water intrusion, mixing effects,

ion exchange reactions, water-rock interaction, and human activities. Additionally, the semi-arid climate exacerbates salinization through high evaporation rates, concentrating salts in the soil and water (Sunkari et al., 2021). The elevated concentrations of Na^+ and Cl^- can lead to soil degradation and reduced crop yields (Sunkari et al., 2023). The presence of these salts in drinking water sources poses health risks, including hypertension and other cardiovascular diseases (Rakib et al., 2019).

8 Conclusion

Salinization of groundwater is increasing worldwide especially in arid and semi-arid regions, threatening its use for drinking and irrigation. Inland basins of arid and semiarid regions are being impacted by both natural and anthropogenic processes, where dissolution of evaporites is a major cause of elevated salt content. Many of the aquifers in inland basins support irrigation agriculture, an activity that adds salinity to groundwater, and once used to irrigate crops, may cause serious damage to soil and crops.

The Major differences in the origin and management of groundwater salinity in affected inland basins can be summarized according to geographic location as:

- USA: Moderate salinity is caused by irrigation, application of fertilizers and pesticides, and aggravated by large urban centers. Salinity data are appropriate and publicly available. Mitigation is achieved by water saving irrigation practices and groundwater managed recharge.
- Latin America: Moderate salinity is caused by irrigation and internal drainage, aggravated by aquifer depletion. The data availability is scarce and fragmented. Monitoring is limited. Mitigation practices include incipient, small-scale, water saving practices in irrigation.
- MENA: high salinity caused by dissolution of evaporites and extreme evaporation rates, aggravated by crop irrigation. Data availability and monitoring are scarce. Mitigation is achieved by adjusting water from different waterholes to meet salinity requirement.
- Asia and Oceania: Moderate to high salinity caused by fertilizer application. Data availability is moderate. Mitigation practices include construction of drainage ditches and canals.

Arid and semiarid regions are facing an increase in groundwater salinization, a process expected to be worsened by global warming. A comparison of salinization rates between locations (wells) is a difficult task due to the high spatial variability in water quality and scant monitoring data. Local and global experts advocate for the development and implementation of more effective salinity management and mitigation strategies, which rely in an appropriate amount of monitoring data as well as the standardization of salinity units. Strategies more commonly sought in these regions are water-saving agricultural practices that reduce evaporation, such as drip irrigation and groundwater depth management. Regarding water quality, infiltration of contaminants from the surface (e.g., fertilizers, herbicides) could be contained to lessen groundwater contamination, however natural contaminants are more difficult to suppress, as shown in the Mexico's example. Reducing natural salinity requires either dilution with fresher water or applying a water treatment such as reverse osmosis.

9 Data availability statement

The supplementary data, including raw data files and code used for analysis, are available upon request from the corresponding author.

10 Ethical statements

This study does not involve human or animal subjects. Ethical approval was not required for this research. All data used were publicly available or obtained through proper channels, with consent where applicable.

11 Conflict of interest

The authors declare no conflict of interest related to this study.

12 Acknowledgement

The authors thank the reviewers for their time and commitment.

13 Author contributions

Gutierrez and Sunkari conceptualized the study, conducted the data analysis, and wrote the original draft. Mickus reviewed and edited the manuscript and assisted with the interpretation of results. Okyere assisted with the diagrams and reviewed the manuscript. All four authors approved the final version of the manuscript.

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